Lessons Learned in University Production of CubeSat Propulsion Systems

Mackenzie J. Glaser[1] and E. Glenn Lightsey [2]
Georgia Institute of Technology, Atlanta, Georgia, 30332

The Space Systems Design Lab (SSDL) at the Georgia Institute of Technology (GT) designs and manufactures propulsion systems for CubeSats using green monopropellant and cold gas propulsion technologies. Over the history of building these systems, a variety of off-nominal behaviors and nonconformances have been observed including contamination by foreign object debris, higher than acceptable leak rates, and inconsistent performance. Root cause investigations have been conducted where appropriate for individual systems and the identified root causes have included manufacturing defects, incomplete cleaning processes, and improper parts sizing. This paper collects and identifies historic off-nominal behaviors and nonconformances observed in SSDL-built propulsion systems and discusses the investigations of the root causes of these behaviors. These root cause issues are outlined and compared to present suspected systemic issues in propulsion system production. Root cause issues on each unit are added up based on the larger category of cause including design, assembly and test processes, or facilities used to conduct these processes. Frequency of causes over the whole propulsion program are used to confirm trends in root causes. Based on these trends, best practices are highlighted to prevent failures on future systems and ensure the highest possible quality of hardware.

I. Nomenclature

ASCENT	=	Advance Spacecraft Energetic Non-Toxic
CMM	=	Coordinate-measuring machine
COTS	=	Commercial Off the Shelf
ΔV	=	Change in velocity (m/s)
DMLS	=	Direct Metal Laser Sintering
EDU	=	Engineering Development Unit
FOD	=	Foreign Object Debris
GD&T	=	Geometric Dimensioning and Tolerancing
GSE	=	Ground Support Equipment
GT	=	Georgia Institute of Technology (Georgia Tech)
Isp	=	Specific Impulse
LFPS	=	Lunar Flashlight Propulsion System
MSFC	=	Marshall Spaceflight Center
SLA	=	Stereolithography

[1] Graduate Research Assistant, Georgia Institute of Technology, Aerospace Engineering, Atlanta, GA
[2] David Lewis Professor of Space Systems Technology, Georgia Institute of Technology, Aerospace Engineering, Atlanta, GA

SSDL = Space Systems Design Lab

SunRISE = Sun Radio Interferometer Space Experiment

SWARM-EX = Space Weather Atmospheric Reconfigurable Multiscale Experiment

VISORS = Virtual Super Resolution Optics using Reconfigurable Swarms

II. Introduction

CubeSats increasingly utilize more advanced subsystems to be able to achieve their scientific objectives. A growth in CubeSat propulsion capabilities has been an important part of using CubeSats for increasingly advanced scientific goals. Enabling propulsive maneuvering allows for both CubeSats being used in deep-space applications where they must expend significant impulse to reach their destination orbit, and for precise formation flying missions to be conducted, where several CubeSats work together to take a measurement and achieve the objective of the mission.

Building the propulsion systems that are needed for these kinds of missions can present unique challenges when compared to traditional larger scale propulsion. Firstly, CubeSats are extremely limited in volume. The propulsion systems used to power them will be extremely small and must be able to occupy whatever space is available onboard (often, this also means conforming to the CubeSat shape – which falls counter to the traditional structural rules associated with designing a pressure vessel). Because of the limited volume, all the components on board must be extremely small, which means that they are typically very sensitive to loading, damage, and particularly foreign object debris (FOD). In addition, CubeSat missions typically fall into the category of low cost/high risk missions – most are NASA Class C or D missions. Thus, the development cost of these propulsion systems will be low, and they often will not undergo full-scale testing that more expensive systems might. The low cost of these missions also means that commercial off the shelf (COTS) part will be heavily utilized in developing these systems, and commercially available parts are often not designed for space-specific applications. Space applications require very high reliability, but the constraints associated with these missions may mean that the parts used will not be tested to the high reliability standard levied on more costly missions.

The Space Systems Design Lab (SSDL) at Georgia Tech has been engaged in the production of CubeSat propulsion systems since 2016. These propulsion systems are designed, assembled, and tested in-house before being delivered to either external or internal CubeSat customers.

III. SSDL Propulsion System Design

The SSDL develops propulsion systems which fall into two primary categories: cold gas propulsion systems, and green monopropellant propulsion systems.

A. Cold Gas Propulsion

Cold gas propulsion systems are a relatively simple type of chemical propulsion. In the simplest versions, a tank of gas is attached to a valve and nozzle, and impulse is achieved by opening the valve to expel gas from the nozzle. SSDL-built cold gas systems are slightly more complicated because of their use of the propellent R-236fa, which is a refrigerant stored as a saturated liquid. This propellent was chosen for its high volumetric specific impulse, which is valuable in a volume-limited CubeSat application [1]. In these systems, the propellent is stored in the main tank as a saturated liquid, then is passed into the plenum to vaporize into a gas before being expelled out the nozzle, ensuring that only gas will be expelled. Figure 1 shows a schematic of a representative SSDL cold gas propulsion system.

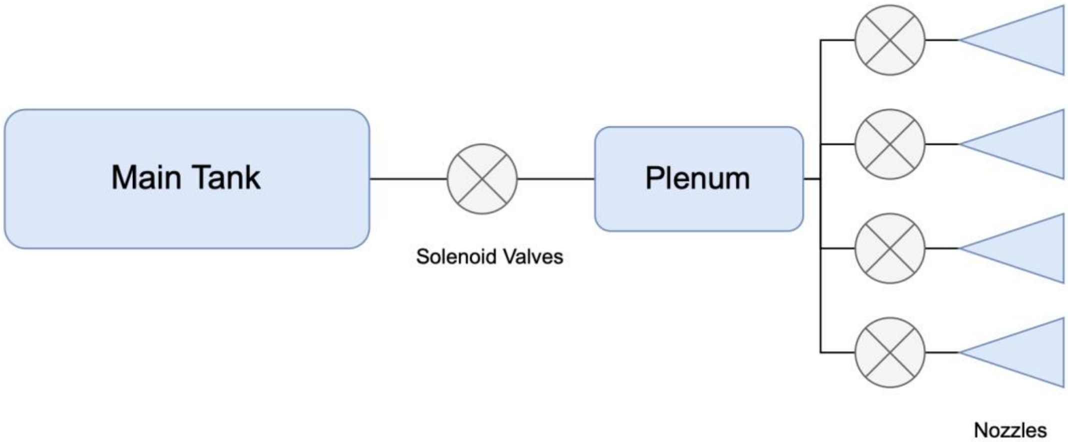

Figure 1. Cold Gas Propulsion Schematic

These cold gas systems are relatively simple compared to systems where a combustion reaction takes place, and so their overall efficiency is lower. Table I shows performance data for an average SSDL cold gas propulsion system utilized on a 6U CubeSat.

Table I. SSDL Propulsion System Performance

	Isp (s)	ΔV for 6U System (m/s)
Cold Gas Propulsion	42.0	11.22
Green Monopropellant Propulsion	~210	>200

SSDL cold gas systems utilize a stereolithography (SLA) printing process with a resin called Somos Perform to manufacture the primary structure, and by doing so can include the main tank, the plenum, all routing between components, and the nozzles themselves as a part of one continuous piece. Utilizing additive manufacturing heavily also allows for the formation of complex geometry in the structures. Any available space on the satellite that could be occupied by the propulsion system can be utilized as a part of the tank volume, since these systems are not restricted to simplistic shapes. Once the structure has been printed, the components can be bolted into it, and the system is complete. Generally, pressure and temperature sensors are screwed into metal plates, and valves for each nozzle are assembled using metal blocks, then all the metal components are fixed to the structure [2]. Figure 2 shows the SunRISE propulsion system in its assembled state.

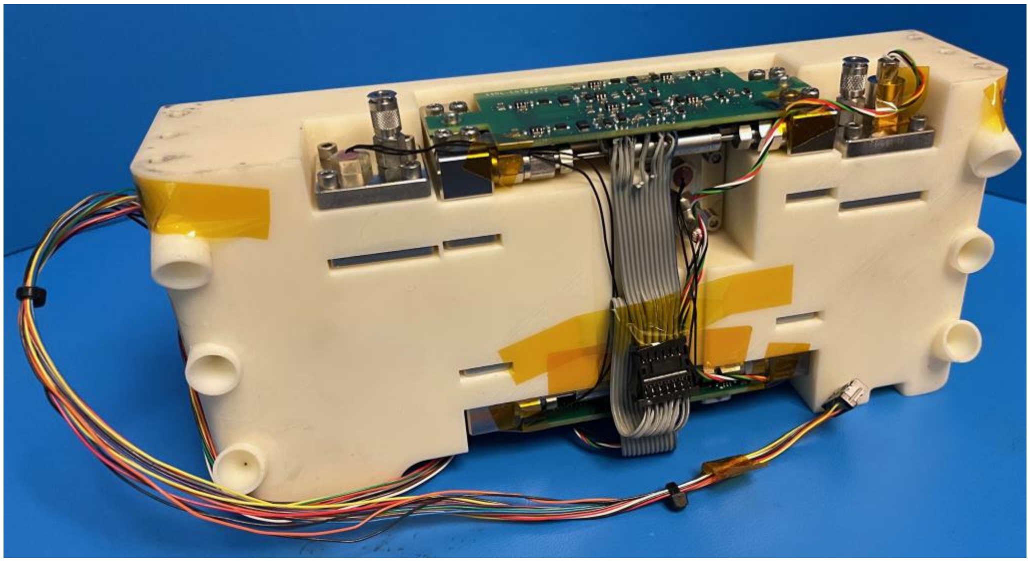

Figure 2. SunRISE Propulsion System

After being assembled, the cold gas propulsion systems undergo a variety of tests to ensure their functionality. First, a basic electronic functional test is run to ensure the boards are functional and correctly interfaced to the valves and sensors onboard. Next, a proof pressure test is run using nitrogen to ensure there are no gross leaks and the structure is sound. Afterwards, the systems are filled with propellent. Some programs require every individual system go through a vibration test (as opposed to some which integrate the propulsion system and then vibration test the whole spacecraft). For the systems which require a vibration test, that test is done next. Then, the systems will undergo a full-length leak check to ensure they meet the leak rate requirement set for them. They are put into the vacuum chamber for 72 hours, run through a hot and cold temperature cycle at high vacuum, and their masses before and after are compared to determine the leak rate. Finally, system performance is measured and compared to theoretical results. Using a specially developed horizontal pendulum thrust stand, the impulse, thrust, and specific impulse (Isp) delivered by the systems can be measured [3].

SSDL's production of these systems began with the BioSentinel propulsion system for NASA's BioSentinel mission. This mission is studying the impacts of deep space radiation on yeast [4]. This propulsion system was delivered to NASA in 2018 and flew to space in 2022 as one of the CubeSats deployed from the SLS during the Artemis I mission. Next, SSDL produced the ASCENT propulsion system for the Air Force Research Lab and delivered it in 2019. This satellite has been in space since 2022.

SSDL is also currently delivering propulsion systems for JPL's Sun Radio Interferometer Space Experiment (SunRISE) mission, as well as the NSF missions: Virtual Super Resolution Optics using Reconfigurable Swarms (VISORS) and the Space Weather Atmospheric Reconfigurable Multiscale Experiment (SWARM-EX). SunRISE will fly six, 6U CubeSats in a formation to form one large single-aperture radio telescope to study radio emissions in the Sun's atmosphere [5]. These propulsion systems are being delivered in early 2023 and scheduled in fly in early 2024. VISORS will fly two 6U CubeSats to form an optical telescope – the spacecraft will fly a set distance apart, with one forming the optics, and the other forming the detector for the telescope [6]. The propulsion systems for this satellite will deliver in mid-2023. SWARM-EX is an additional formation flying mission composed of three 3U CubeSats, which will study the Equatorial Ionization Anomaly and the Equatorial Thermospheric Anomaly [7] which is also planning for a 2024 flight.

B. Green Monopropellant Propulsion

Monopropellant propulsion systems utilize a single propellant that undergoes a chemical decomposition when run over a heated catalyst bed. The chemical reaction allows these systems to produce more efficient impulses when compared to cold gas systems, but also makes them more complicated. Traditionally, the most common monopropellant to be utilized is Hydrazine, but this propellant is highly toxic, which makes it dangerous and costly to work with. In recent years, less toxic monopropellant fuels have been developed, and dubbed "green monopropellants." One of these propellants is AF-M315E, also referred to as ASCENT.

In 2019, SSDL began the design of a propulsion system for JPL's Lunar Flashlight Mission, the Lunar Flashlight Propulsion System (LFPS). This mission was designed to study water ice at the Lunar south pole and launched in December of 2022 [8]. The propulsion system designed for this mission was SSDL's first to utilize the ASCENT monopropellant propulsion technology. The performance characteristics of this system are shown in Table I.

Because of the constraints on use of the propellent, components were needed in the system that were different than the cold gas systems. Thrusters were procured for this system from a vendor called Plasma Processes; the thrusters have strict requirements on inlet pressure, so a pump with a recirculation loop for relief needed to be included in the system to provide the desired pressure. The inclusion of the pump allowed propellant in the tank to be stored below 100 psi, and thus not be characterized as fracture critical [9]. The schematic for the LFPS can be seen in Figure 3.

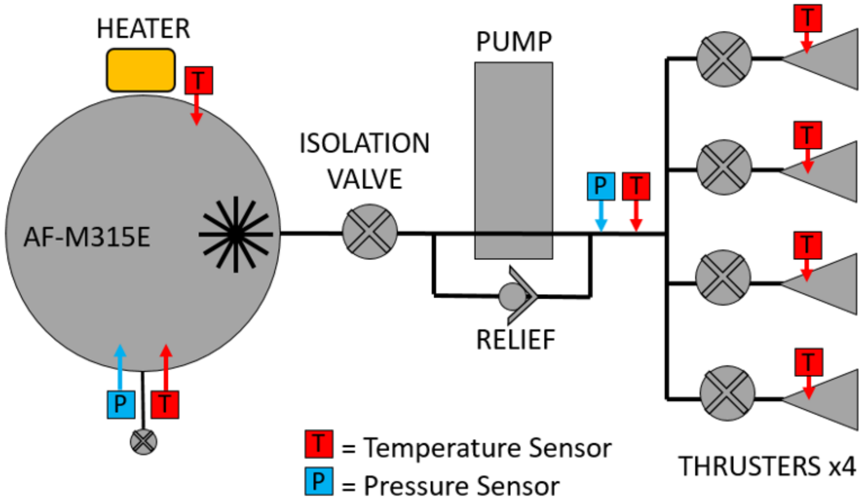

Figure 3. Lunar Flashlight Propulsion System Schematic [9]

The primary structure of the system consists of a machined tank, and an additively manufactured manifold, which bolts to the tank and allows all fluid routing between components to be done internally. The manifold is additively manufactured from titanium through a direct metal laser sintering (DMLS) printing process. This manufacturing allows the system to remain relatively compact, as opposed to having to run tubes between each individual component.

The LFPS was assembled over the course of 2020 and 2021. Through the assembly process, first the parts were procured, internal components to the tank were installed, and the tank halves were welded together. Then, components on the manifold like the valves and sensors were assembled to the manifold, components on the tank were assembled to the tank, and finally the tank and manifold were mated together. At each of these steps in the process, a pressure test was conducted to ensure the subassembly could meet its proof pressure, and there were no gross leaks. Then, the pump, controller boards, thrusters, and cover were installed, and the whole unit was tested as an assembled system [11]. The assembled LFPS is shown in Figure 4. The tank is the rectangular shape sitting on the table, and two of the four thrusters can be seen mounted on top of the manifold which is sitting on the tank.

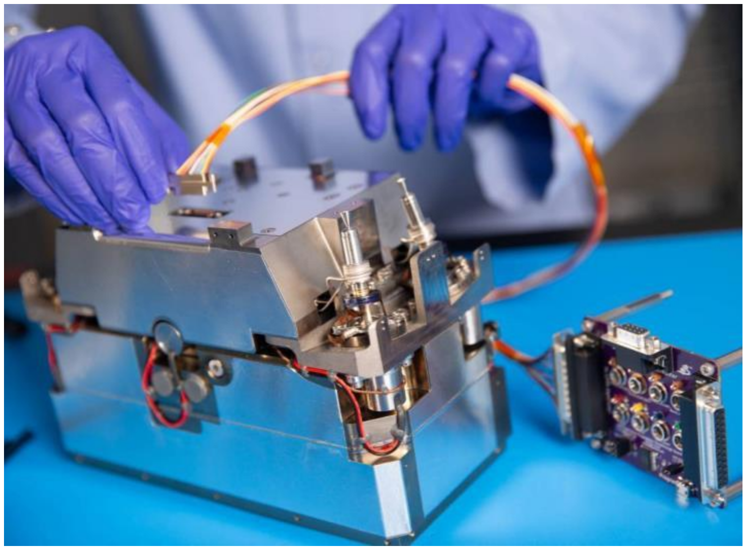

Figure 4. Lunar Flashlight Propulsion System

After assembly, LFPS underwent full functional checkouts of the controllers and software, a system level leak check utilizing helium and a mass spectrometer, and a variety of functional checkouts on individual subsystems including each of the system heaters. The propulsion system did not undergo full performance testing as an assembled system.

Following the build of the LFPS flight unit, the teams at NASA MSFC and GT decided to build a second unit of the system, utilizing hardware that had been procured during the build of the first. LFPS SN002 began build in the latter half of 2021, but due to delays and hardware nonconformances which will be discussed in this paper, is expected to be completed by June 2023.

IV. History of SSDL Propulsion System Nonconformances

A. Nonconformance Generation

When a system exhibits any kind of off-nominal behavior either in build, in testing, or in flight, the nonconformance documentation process is triggered. Generating a nonconformance involves careful documentation of the issue observed and evaluation of a path forward. Evaluating the path forward includes investigating the root cause of the problem: by running further tests, doing further inspections, checking documentation, and working with vendors. Once a root cause has been identified, both the fix on the nonconforming unit can be chosen, and any changes that can be made going forward to prevent the root cause from damaging other units should also be documented and implemented. SSDL has a formal process for documenting nonconformances on flight hardware, and these processes are followed on flight programs.

B. Nonconformance Categorization

In this paper the approximately 30 nonconformances that have been documented on flight projects are examined. These nonconformances come mostly from the LFPS and SunRISE programs, as those programs have delivered hardware and had the most mature documentation requirements at the time of their assembly. These 30 nonconformances can be grouped by the basic issue observed into a few primary categories, as shown in Figure 5.

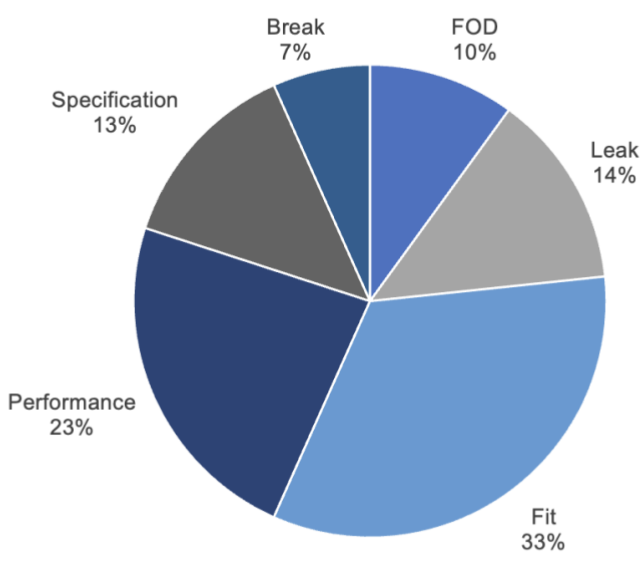

Figure 5. Nonconformance Categories

The categories can be described as follows. Fit nonconformances are those in which two or more designed parts fail to fit together properly, or a part is not properly sized for the interface it is supposed to meet. Performance nonconformances are those in testing or flight when the system is unable to meet its specified performance goals. Leak nonconformances are those when the pressure vessel is unable to hold a proper seal and propellent leaks out during testing. Specification nonconformances are somewhat unique – they are triggered when a system is unable to meet the requirement or tolerance specified, but the nonconformance is given a use-as-is disposition. These nonconformances are generated as a result of a poor requirement on the system that it does not need to meet in order to complete its mission. FOD or foreign object debris nonconformances are ones where a precision cleaned part is visibly dirty: FOD can also be a cause of other categories nonconformances, but this category is specifically for the initial observation being FOD. Finally, a break nonconformance is one where a part has broken, typically seen during the assembly process.

The following sections describe a selection of significant and noteworthy nonconformances observed during the assembly, integration, test, and flight of SSDL propulsion systems. These do not make up a complete list of all nonconformances observed in each category.

C. Fit Nonconformances

SunRISE exhibited a significant fit nonconformance in the design of its O-Ring grooves. One of the systems had to be disassembled for rework after testing, and when it was disassembled, it was discovered that the inner wall of the O-Ring groove on the structure had failed and was no longer attached to the structure, as shown in Figure 6. The ring being held in the image is the O-Ring groove wall which should sit where the red circle is. This could cause an improper seal and could also contribute to FOD contaminating the tank. After investigating the failure of this part, it became obvious that the O-Ring groove was improperly sized for the O-Ring being used. It was close enough to appear correct when assembled, but the groove was too narrow which resulted in too much pressure being applied to the inner surface by the O-Ring causing it to break. For the already constructed units, the inner O-Ring grooves were machined off the structure, and the inner groove was instead added to the block which interfaces to that port – allowing the program to proceed without rebuilding the structures. An audit was conducted of other cold gas programs to ensure these design errors were corrected elsewhere, since they had been flowed down from a heritage design.

Figure 6. SunRISE O-Ring Nonconformance

LFPS also exhibited several fit nonconformances which required rework. When the manifold returned from manufacturing, it had several hole positions that were out of the specified tolerance. Some of the holes had been dimensioned from printed surfaces instead of machined surfaces, which resulted in holes not being correctly aligned with the part of the printed structure they needed to be. These holes had to be re-drilled in their correct locations by referencing alternate datums. Several similar out-of-tolerance nonconformances were seen throughout the LFPS program.

Additionally, later in assembly an interference was discovered between the wire route and the corner of the tank that posed a risk to the wire. Because the wire route had not been carefully modeled in the original design process, this problem was not noted until actual assembly. The corner had to be drilled out and filed significantly to allow for the wire to route by it without any risk. To correct this problem going forward future systems should include wire routing from the initial design phase. The post-machining wire route is shown in Figure 7, and the circular cutout added to allow the wire to route as needed can be seen [12].

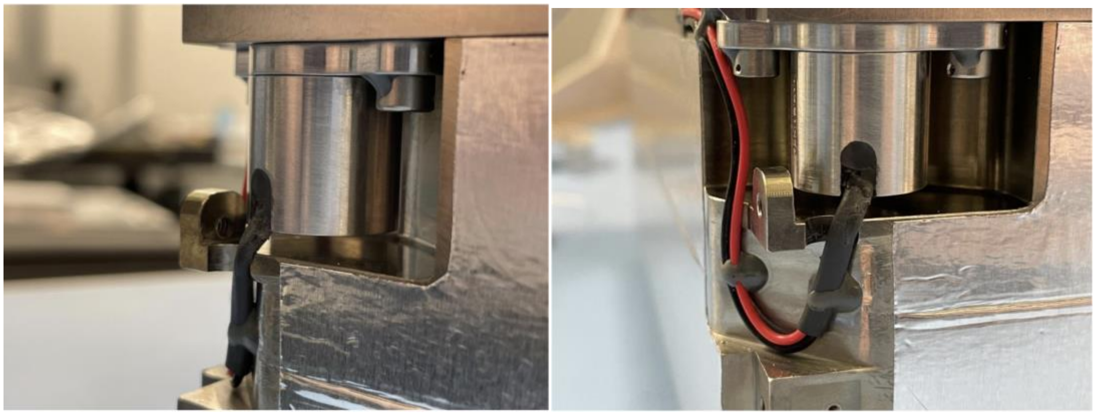

Figure 7. LFPS Wire Routing Defect Fix

D. Performance Nonconformances

Performance nonconformances were one of the largest categories of nonconformance recorded throughout the program. The SunRISE propulsion systems have struggled with a range of performance nonconformances, starting from the first propellant fill of the first flight unit. The SunRISE units use the socket end of a quick-disconnect on the structure to allow a fill harness to be mated to the system for propellant fill. By design, when not mated to the other side quick disconnect, the quick disconnect connected to the unit will spring closed. When the flight unit was filled, and the fill harness was disconnected, the quick-disconnect stayed open, and allowed propellent to spray rapidly out of the system.

After numerous attempts to manually manipulate the quick disconnect into closing, the system was allowed to drain of propellent while the issue was investigated. Eventually, the system was disassembled to allow for a more thorough inspection and disassembly of the quick-disconnects themselves. Disassembly, inspection, and subsequent work with the vendor revealed that these parts had an internal spring that was made of a weak material and could be permanently deformed resulting in the quick-disconnects sticking open. The vendor has since updated the spring material for future units, and the SSDL programs which use this part have implemented testing campaigns to ensure every unit works correctly before it is installed into flight hardware. Figure 8 shows the poorly behaving quick-disconnect and the spring that contributed to its failure.

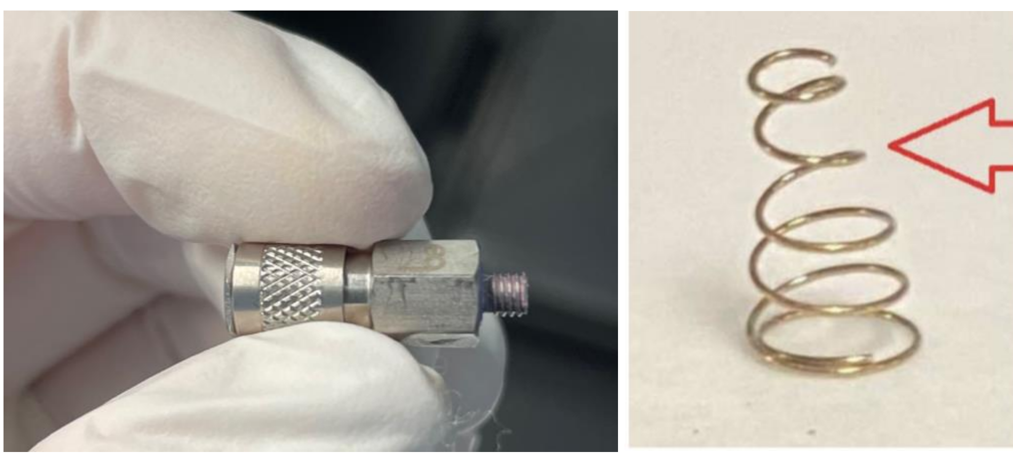

Figure 8. SunRISE Quick Disconnect Nonconformance

The SunRISE program also saw underperforming units early on in the performance testing process. Several SunRISE units experienced valve stiction issues which were partially remedied by regular cycling of the valves, as well as an improvement to the valve driver circuit to boost the spike voltage the valve received.

Additionally, some SunRISE engineering development units (EDUs) had problems where during performance testing, one nozzle would significantly underperform the others as shown in Figure 9 with Nozzle 5. Inspection of the valves and electrical testing revealed the issue had to be a physical obstruction in the flow path attenuating the flow to the nozzle. Several SunRISE EDUs were inspected and tested, and the problem was revealed to be twofold: first, the filters in the flowpaths had varying mass flow rates they would allow – some obstructed the flow significantly more than the others. Going forward, these filters were screened out of the flight parts with some testing prior to assembly. Secondly, some units had print defects leading to blocked passages.

These blocked passages occur in the printing process when the SLA resin is not adequately cleaned from the internal geometry before post-processing. The post-processing process the vendor completes includes a curing step, so if any resin is stuck in the part, it can be cured by the curing step, and remain stuck inside the structure: potentially attenuating flow or blocking a passage altogether. An example of a blocked passage can be seen in Figure 9. This image was taken with a CT scanner, and the blocked passages are circles in red. The solution to this problem is to adequately clean the print after the printing process but prior to the curing process. On SunRISE, the engineering team worked with the printing vendor to implement a rinsing process at their facility. Using syringes, the structure and internal channels were rinsed first with a cleaning agent and then with isopropyl alcohol prior to the cure, and this solution was able to prevent this problem on subsequent units.

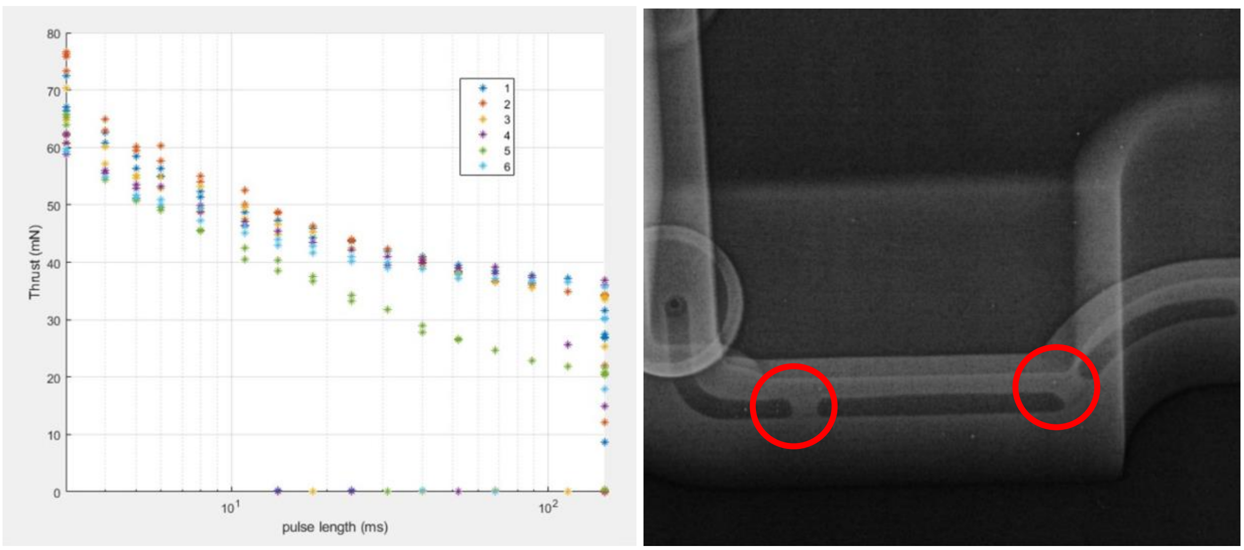

Figure 9. SunRISE Performance Data and Blocked Passage

LFPS also has the most significant example of a performance nonconformance, with its recorded behavior in flight. The CubeSat launched in December of 2022, and soon after beginning propulsive maneuvers, began to exhibit lower than expected impulses from some of the nozzles. Eventually, all nozzles exhibited highly degraded and unpredictable performance. Based on the behavior of the system, the root cause of this issue was eventually identified as FOD: particulates getting caught in the thrusters and attenuating or fully blocking the flow through them.

Though it is impossible to know with the spacecraft in flight, it seems likely that this FOD was a result of the additive process used to manufacture the manifold. Similarly to the SLA process, the DLMS process has post-processing steps done after printing. The printing is done from a metal powder, and after the printing, the parts must be heat treated to a relatively high temperature to relieve stresses induced in the printing process. If powder from the printing process remains, this powder can be partially sintered onto the structure, and stay inside the structure during the build process. After undergoing vibrational loads from launch, this partially sintered powder could break free from the structure and become FOD in the tanks. This partially sintered powder appears to be the most likely source of FOD on the systems, but another is the precision cleaning process itself. This process was done at a vendor, and it is possible that the complex internal geometry was not adequately cleaned since the process was not directly monitored by SSDL engineers.

E. Leak Nonconformances

Leak nonconformances are a type of nonconformance commonly seen on propulsion systems, since propulsion systems are pressure vessels with multiple sealing surfaces that all need to seal in order to work correctly. It’s important that system level leak rates be low so that the spacecraft retains enough fuel to complete its mission and avoids any unaccounted for momentum being added in flight due to the impulse coming from the leak.

One large leak was discovered on the LFPS SN002 system after that system was fully integrated and undergoing its leak rate check. Even when the valve was closed, helium was leaking past the valve, and exiting the system through the nozzle. The system was disassembled, and the structure was inspected to determine the cause of the leak. After a careful inspection, the team determined that there was a scratch in the O-Ring groove of the leaking valve, allowing fluid to entirely bypass the valve even when it was closed. This scratch was difficult to see on inspection, but could be felt with the use of a dental pick. After finding the scratch, the system was re-machined to put in a smoother groove. Similar small O-Ring groove scratches can be seen in Figure 10.

Figure 10. LFPS O-Ring Grooves with Scratches

Leaks were also periodically seen on the cold gas programs, including BioSentinel, SunRISE, and SWARM-EX [13]. On these systems' EDUs, higher than expected leak rates were observed during vacuum chamber leak rate testing. Eventually, these leaks were identified to be coming from the interfaces of the valves with the fittings used the screw them into the systems. All used swage type fittings to interface to the structure, and the standard swaging process was not sufficient to seal these fittings against the valve stems. A process was implemented where after being swaged once, the valve manifolds were connected to a gas source, then checked for leaks at the swage joints using Snoop liquid leak detector. The sizes of the leaks at each of the sources were identified, and they were re-swaged until the leaks stopped. This process was able to bring the leak rates of these systems into tolerance, but going forward, the choice of fittings used on these systems may no longer be appropriate, given their standard leak rate. Figure 11 shows the process of leak-checking these manifolds to ensure that there are no leaks at the swage joints.

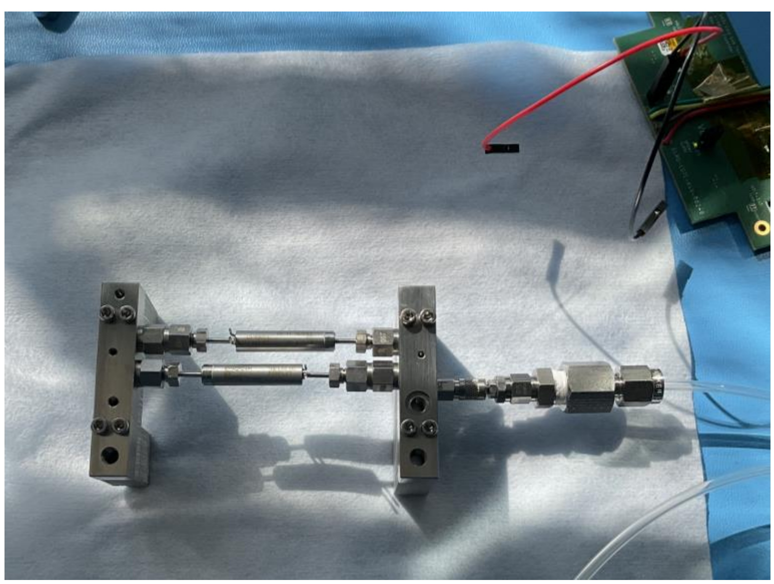

Figure 11. Manifold Swaging Leak-Check GSE

F. Specification Nonconformances

Specification nonconformances mostly deal with poorly written requirements or requirements that are waived after the nonconformance process is completed. About 50% of the specification nonconformances recorded have to do with tolerances given on engineering drawings. One example comes from LFPS, where many holes on the tank were slightly out of tolerance when it went through the coordinate-measuring machine (CMM) inspection process. Being out of tolerance triggered a nonconformance on the SSDL side, but it was eventually determined that the part could be used as is with no issues. The nonconformance resulted in a change to the drawing, not the part, and loosened the tolerances required if this part is manufactured again.

Another example of a specification nonconformance is a failure to demonstrate a requirement has been met during a test. On one LFPS proof test, an operator mis-read a pressure requirement as 500+/-5 psi, and took the unit to 495 psi, when the requirement was actually 500+/-1 psi. Even though this test was not conducted as written, due to it being an intermediate test, and the pressure being tested already having a large factor of safety on it, the choice was made to not complete a new test and put another pressure cycle on the equipment to merely increase the pressure by 4 psi. This specification nonconformance was a clear operator error. In future procedure revisions, the requirement should be listed immediately beside the box to record the pressure achieved and should require a peer review step.

G. Foreign Object Debris Nonconformances

Foreign object debris nonconformances are those where FOD is directly observed on a piece of precision cleaned hardware. One significant case of this was seen on the LFPS SN002 manifold. When the manifold was returned from the cleaning vendor after the O-Ring groove rework was complete, a piece of FOD was immediately spotted inside a flow path during inspection. What was seen during inspection, as well as some of the FOD after removal from the system is shown in Figure 12.

Figure 12. FOD in LFPS SN002 Manifold

This FOD indicated that the manifold was not cleaned to specification by the cleaning vendor. The manifold was shipped to NASA MSFC to be re-cleaned, and the cleaning vendor will not be used on any future SSDL propulsion systems. It is important to note here that the LFPS flight unit and the SN002 unit were cleaned by the same vendor. Though the printing process may be at fault in the LFPS flight nonconformance, confidence in this vendor's ability to clean internal geometry is very low as a result of this FOD discovery (discovered after the launch of Lunar Flashlight).

H. Break Nonconformances

Break nonconformances occur when a piece of hardware physically breaks, typically during the assembly process. Relatively few of these were observed across the propulsion program, but there are two significant examples from LFPS. The first was a broken propellant management device due to improper torquing. Early in the build process, the LFPS team did not have strong backgrounds in torque wrench usage. The propellent management device was torqued into the structure, but did not reach the specified torque value it should have. As a result, it had to be un-torqued and re-torqued again. During the un-torquing process, a piece of the device snapped off, as it was never meant to be removed once attached. It was replaced with a new device for the next install. Another example of a break nonconformance occurred in the testing phase. While being moved from one fixture to the next, the connector on the end of a valve wire snagged inside a channel on a nearby fixture. The snag was very gentle and after inspections of the connector and conductivity tests, was deemed acceptable to use as is. Going forward, the team was more careful to adequately secure wires. Both of these integration anomalies were ultimately caused by inexperienced operators who did not know the potential risks. Less experienced personnel are an inherent part of working at the university level, but since these incidents, the internal SSDL training program to be allowed to work with flight hardware has advanced significantly.

V. Nonconformance Root Causes

Identifying root causes is essential to the nonconformance process, and the examples included in Section IV discussed briefly the process of identifying the root causes of each issue, and the causes that were identified. All the nonconformances studied in this report, were grouped into four primary categories: COTS parts, manufacturing defects, design mistakes, and errors by integrator. These categories break down as shown in Figure 13.

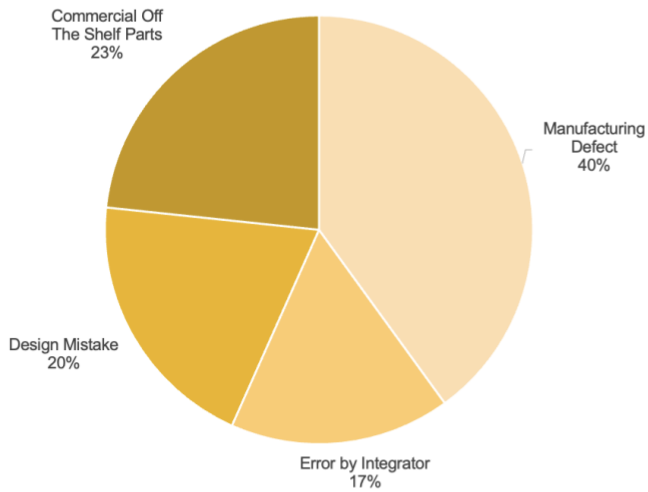

Figure 13. Nonconformance Root Causes

Manufacturing defects make up the largest root cause category. Inside this category, the most prominent manufacturing defect is machining errors with problems like holes being drilled in the wrong place, improper surface finishes on parts, or burrs not being removed. Additionally, 25% of manufacturing defects were cleaning related defects meaning the part was sent to a cleaning vendor but not returned cleaned to specification. Finally, another significant portion were problems in additive manufacturing. Across both the cold gas and green monopropellant programs, additive manufacturing is heavily utilized to print SLA resin on cold gas and DMLS titanium on monopropellant. Though the methods are different, both share a similar issue: when the structures come off the print, if their internal geometry is not adequately cleaned before post-processing, it can result in blocked passageways, or the generation of FOD.

COTS parts make up the next largest category. These root causes mean that a vendor part is not meeting its specification or performing its intended function. These root causes have included: valves that do not open properly, fittings that leak, filters with drastically different flow speeds, and improperly installed connectors. In this category, when a part malfunctions, SSDL often collaborates with the vendor to determine the extent of the issue and whether the part can still be utilized. Generally, once the stage of the process is reached where a vendor part problem is detected, the hardware has already been designed and procured, so it is often best to find in-situ fixes rather than attempt to change the part used entirely.

Design mistakes are a root cause when the engineer should have been able to prevent the nonconformance through proper design practices. In this category are problems such as parts that by design interfere with each other, parts not being properly sized for the fasteners or seals that interface to them, engineering drawings being improperly produced leading to faulty parts, and problems with basic system design that the concept of operations must work around. When these problems are a root cause, there is a very clear lesson learned that can be applied to future systems – sometimes the current system has to be redesigned and sometimes it must be reworked.

Errors by integrator are problems whose root cause exists in the integration phase, as opposed to the manufacturing phase. In a build program, it is impossible to prevent all integration misses (things like a wire being slightly tugged, or a misinterpretation of a test requirement on paper), but several of the nonconformances identified as having this root cause have to do with integrator training (how to properly use a torque wrench, how to properly assemble fittings). As a university based program, the assemblers are not industry experts, and thus do not begin their roles with years of experience in spacecraft assembly. The training program designed to prepare students for spacecraft assembly has grown significantly in the past several years, but lessons learned from this category of root cause can be used to bolster the training requirements for operators, as well as improve the clarity with which procedures for hardware work are written.

VI. Lessons Learned to Prevent Future Nonconformances

A. Nonconformance Identification

One critical area to understand in prevention of nonconformances is at what stage in the process of producing hardware those nonconformances are caught. Figure 14 illustrates the breakdown of where the documented nonconformances were caught. Based on the figure most nonconformances are caught either in performance (i.e. a bad test result or poor in-flight performance), or during an inspection of parts. Nonconformances being caught during inspection is the ideal scenario: generally, inspections are happening on individual parts, prior to time being spent assembling those parts. When problems are found, parts can go through additional fabrication steps to resolve the nonconformances without having to disassemble whole propulsion systems. When nonconformances are identified in performance, it is either because the system is already in flight (in which case it cannot be remedied), or because a problem was seen in testing. When it is a problem in testing, normally the unit must be at least partially disassembled to identify and correct an underlying issue. Thus, catching nonconformances during inspection significantly reduced time required to rework and correct a problem on a system.

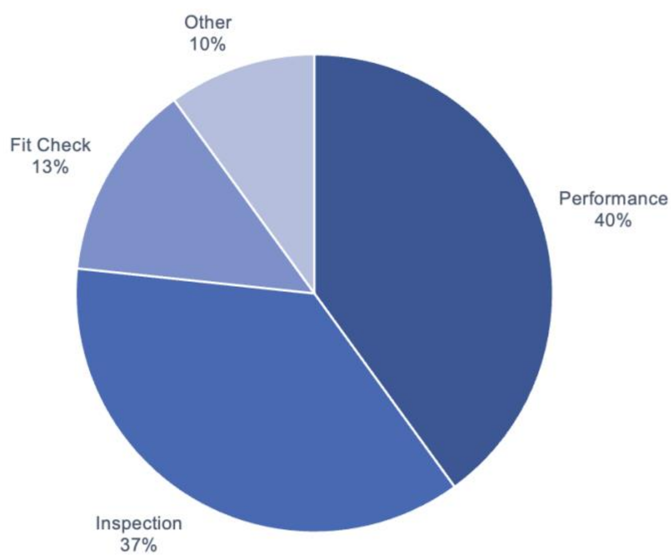

Figure 14. Nonconformance Identification Point

Evaluation of the nonconformances that were identified downstream of inspection (either in fit check, performance, or elsewhere) found that approximately 37.5% of the nonconformances caught downstream of inspection could have been caught earlier with a more thorough inspection process. That makes up a significant portion which could be easier, quicker, and less costly to rework, if a more thorough inspection had been performed.

In order to prevent these inspection misses, a thorough inspection procedure should be written that includes inspection requirements for all hardware upon receiving. It should include sections conditional on the type of parts being inspected, including special inspection processes for:

1) Sealing surfaces like O-Ring grooves
2) Visual cleanliness, and cleanliness after swabbing
3) Threads of components
4) O-Ring surfaces
5) Machined part surface finish, sharp edges, and burrs
6) Additive part internal passages

All of these inspections should utilize not only visual means, but magnification, and other tools like dental picks and swabs to feel rough edges and pick up contaminants. These processes must happen as soon as parts are received, as any delay in an inspection which notes a nonconformance will just delay the project further.

B. Preventing Manufacturing Nonconformances

An inspection process like the one described above is key to detecting manufacturing nonconformances. As soon as parts are returned from a manufacturer, they should go through the standardized SSDL inspection process to be checked for defects, as well as be dimensionally verified or fit checked as soon as possible. Adding these steps early in the process will allow adequate time for rework and catch mistakes before parts are integrated.

Preventing manufacturing nonconformances can be more difficult to navigate; most manufacturing processes occur outside of SSDL, since SSDL is not a large production facility. Thus, communicating and working directly with the technicians and machinists completing the work can be challenging. Investing in relationships with trusted vendors and communicating that this hardware is intended for spaceflight applications are important parts of making sure hardware is treated with adequate care and concern. Open lines of communication are important in both directions, as any non-industry-standard drawing practices done by the design team at SSDL can be open to misinterpretation and lead to nonconforming parts.

On drawings, particular attention should be paid to requirements around removing burrs and sharp edges, tolerancing of holes, and surface finishes. Without requirements applied to the drawing and communicated with the shop, these defects will not be removed, and parts may exhibit some of the traits seen in Figure 15.

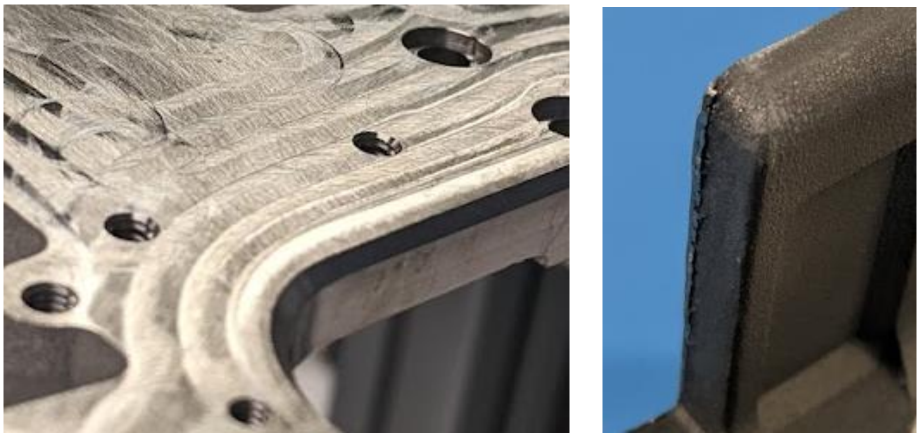

Figure 15. Poor Surface Finish and Burrs on LFPS Component

For prevention of nonconformances in the additive manufacturing process, there should be clear communication to the vendor about the concern with material left behind prior to post processing and the risks it causes for the mission. When appropriate, SSDL should work with the vendor to design any GSE that may make the process of cleaning the interiors easier, or even send an engineer to observe the process and assist. The SunRISE program sent engineers to the additive vendor used, and those engineers implemented a process of rinsing the internal geometry of the SunRISE units with a cleaning solution and isopropyl alcohol prior to post-processing the structures. Since the implementation of this process, no additional blocked-channel defects have been seen, this fix just required working closely with the shop over a matter of weeks.

Cleaning nonconformances are another of the most common manufacturing nonconformance types. The vendor previously used on certain programs is not reliable enough to continue to work with SSDL. Instead, a reliable vendor should be identified, and when parts are sent to them to be cleaned, SSDL engineers should work closely with the cleaning team to:

1) Define the necessary cleaning standard for the project
2) Communicate that internal geometry exists and is the most essential part to be cleaned
3) Determine a strategy and procedure for cleaning (and sampling) the internal geometry
    a) Including an order of operations that is likely to result in clean internals
    b) Including the development of any GSE needed to allow cleaning fluid to be flowed inside
4) Collect the data including the sampling numbers taken, and images and procedures of the interior structures being processed

C. Preventing COTS Part Nonconformances

Because most CubeSat missions are relatively low cost, it is impossible to avoid the use of COTS parts in CubeSat propulsion systems. COTS parts can be highly effective in many applications, but should be approached with caution for use in space. COTS parts not specifically for spacecraft uses will not always behave as intended, and some number of them will exhibit a nonconformance over the course of a program.

An important part of utilizing COTS parts on spacecraft is institutional knowledge about trusted suppliers, and part performance on past systems. Within SSDL, most of this knowledge has not been formalized, and due to high turnover rates among engineers (as a function of being a university program), knowledge can be lost between programs. To formalize this knowledge and make it more accessible for future teams, a database of current institutional knowledge around COTS parts is being written and will be kept in a location accessible to all future SSDL propulsion engineers.

Especially when utilizing COTS parts with no history within SSDL, several steps should be taken to decrease the chances of a nonconformance on that hardware. Following the rule of always assuming the COTS parts will not function as intended, spares should always be purchased when parts are procured. This will allow for testing of spare parts and will allow for parts to be switched out if one unit is discovered to be nonconforming without having to wait the procurement time again. Steps should also be taken to test the COTS parts when possible. Truly testing-like-you-fly a COTS part can have very high overhead, but simplified tests can be run to ensure it is within conformance. A simplified test for a valve could include hooking it up to a pressure system and opening and closing it 100 times to ensure it always opens and closes. If more extensive testing was required, it would also be hooked up to a system with the proper propellent and cycled to ensure true propellant compatibility. Fittings should undergo a basic leak check when being procured for the first time, and quick disconnects should be connected and disconnected from pressurized GSE several times to ensure that they properly close when disconnected.

EDUs are also a valuable tool for verification of COTS parts. Including an EDU in the contract cost should always be a priority and developing the EDU with enough time to run adequate testing on it and make any necessary changes to COTS parts will also help increase overall system reliability.

D. Preventing Design Mistakes

Design mistakes often fall into the category of engineering training – because the group is a university lab, there is not much design oversight from senior level engineers and mistakes can be made by engineering students that are never caught. In general, design mistakes will be decreased through proper CAD and drawing checking procedures being implemented within the group. These drawing check procedures should not just be to check a box, but should involve truly looking at dimensions of parts, and verifying that interfaces to other parts are properly sized to ensure a good fit it achievable.

A significant number of the nonconformances caused by design mistakes were caused by improper engineering drawing standards. An improper understanding of geometric dimensioning and tolerancing (GD&T) can lead to unclear drawings that results in nonconforming parts. Mistakes such as placing datums on as-printed (instead of machined) surfaces, tolerances that are too narrow to be achievable, and improper callouts for tapped holes can result in generation of nonconformances. Some of these nonconformances must be reworked to allow the structure to meet its function, others are just specification problems, where the part will not pass inspection, but is still functional.

To reduce the nonconformances that are a function of GD&T problems, SSDL mechanical engineers should receive formal training in GD&T. In industry, it is standard to have a GD&T group who checks all drawings and serve as experts, but without such experts in the university setting, students should be able to go through a training outside of the lab to prevent these mistakes.

Other best practices that can be taken to prevent design mistakes are training (from senior lab members) on O-Ring sizing, including wire routing in CAD to avoid sharp edges, putting together CAD assemblies using hole position, and checking assemblies with the interference tool.

E. Preventing Integrator Errors

Integrator errors are generally due to either poorly written and unclear procedures, or lack of training on processes or tooling. Training in these areas has improved within SSDL over the past several years, and best practices and lessons learned are captured here.

Poorly written and unclear procedures can be helped by taking a few steps during writing procedures:

1) Implementing the procedure on an EDU or test hardware, and taking pictures to include
2) Describing steps clearly in addition to pictures, and putting labels on pictures
3) Leaving blanks to document specific numbers like: running and final torques, voltage given, pulses length sent, name of test sequence, pressure,
4) Bolding key numbers or steps, and having the requirement for a peer review signature
5) Having requirements at the top of the procedure
6) Having caution/warning statements at the top of the procedure and on important steps to prevent misses

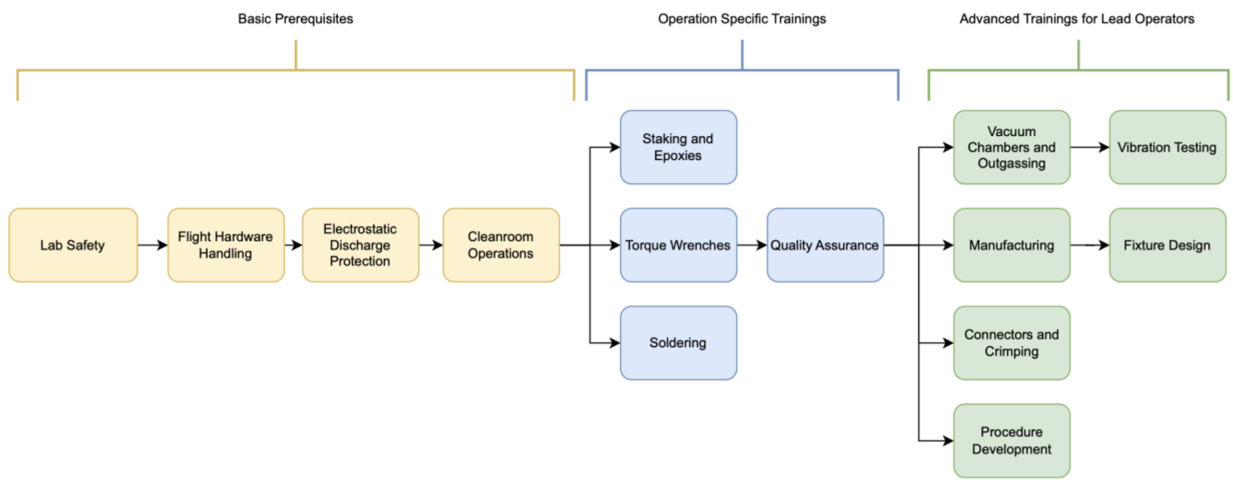

Figure 16. Hardware Training Flow Diagram

Operator process training has been significantly improved by the addition of a spacecraft engineering course dedicated to working with hardware. Key to this training program are: torque wrench training, electrostatic discharge protection training, cleanroom training, epoxy training, and general training on proper fixturing and handling of hardware (avoiding things like wire snags, and drops of tooling or hardware). A suggested flow of required training operations can be seen in Figure 16. Whether through this course or through the lab in general, all SSDL engineers who will be in contact with flight hardware must undergo these trainings to be able to lead flight hardware procedures, and this training should be given and verified by senior engineers in the group.

VII. Conclusion

Developing propulsion systems for CubeSats presents unique challenges, especially with the resources available at the university level. Over SSDL's 5+ year history of building such propulsion systems, a number of nonconformances have arisen and been solved to successfully deliver propulsion systems. Through that process, certain systemic problems have arisen again and again. In order to minimize reworks and deliver the most reliable systems possible, certain lessons learned should be taken into account going forward. Manufacturing defects can be caught through thorough inspection processes, and prevented through close communication with machine shops, printing shops, and cleaning shops. Problems with COTS parts can be prevented by formalizing knowledge about suppliers, procuring spare hardware, and testing all vendor parts. Design mistakes can be prevented through improvements to the student training programs, and careful design reviews, and integrator errors can continue to improve through continuation of the hardware training programs already in place.

Acknowledgments

Thank you to Dr. Glenn Lightsey for the unparalleled opportunities, responsibilities, and guidance you've provided over the past four years. I've learned more in this lab that I think I could have possibly learned anywhere else, and I could not be more appreciative of the opportunities you've given me.

Thank you to my wonderful teammates on the SSDL propulsion team: Sam Hart, Sam Wood, Kevin Tong, Ben Terry, Mohit Singh, Nathan Daniel, Kian Shirazi, Mark Hartigan, Celeste Smith, Lacey Littleton, and Brandon Colón. I have been incredibly lucky to work alongside and learn from this stellar group of people, and they deserve enormous credit for creatively solving the many problems outlined in this paper, and still being joys to work with while doing so.

Thanks to our awesome undergrads: Ashish Cavale, Matt Dembiec, Jalen Cauley, Gabe Nixon, and Alex Fester for the hard work, excitement, and comic relief. And thank you to the prior SSDL propulsion engineers who built the foundation on which this work is based: Dawn Andrews, Ali Talaski, Grayson Huggins, and Terry Stevenson.

Additional thanks to the SunRISE teams at JPL and SDL, and the LFPS team at MSFC. None of this work would be possible without the support of these organizations.

References

[1] Stevenson, T., "Development Of Multi-Functional Structures for Small Satellites," Ph.D. thesis, Georgia Institute of Technology, Dec. 2018.

[2] Shirazi, K. and Lightsey, E.G., "Integration and Testing of a 2U Cold Gas Propulsion System for the SunRISE Mission," Tech, rep., Masers Report, 2022.

[3] Stevenson, T., and Lightsey, E.G., "Design and Operation of a Thrust Test Stand for University Small Satellite Thrusters," AIAA-10.2514/6.2019-2117, 2018 AIAA SciTech Forum, Kissimmee, FL, January 2018.

[4] Stevenson, T., Glenn Lightsey, E., and Sorgenfrei, M., "Development and Testing of a 3-D-Printed Cold Gas Thruster for an Interplanetary CubeSat," *Proceedings of the IEEE*, Vol. 106, No. 3, 2018, pp. 379–390.

[5] J. Kasper, J. Lazio, A. Romero-Wolf, J. Lux and T. Neilsen, "The Sun Radio Interferometer Space Experiment (SunRISE) Mission," 2021 IEEE Aerospace Conference (50100), 2021, pp. 1-11, doi: 10.1109/AERO50100.2021.9438184.

[6] Lightsey, E. G., Arunkumar, E., Kimmel, E., Kolhof, M., Paletta, A., Rawson, W., Selvamurugan, S., Sample, J., Guffanti, T.; Bell, T.; Koenig, A.; D'Amico, S.; Park, H.; Rabin, D.; Daw, A.; Chamberlin, P.; and Kamalabadi, F.; "Concept of Operations for the VISORS Mission: A Two Satellite Cubesat Formation Flying Telescope," AAS 22-125, 2022 AAS Guidance, Navigation and Control Conference, Breckenridge, CO, February 2022.

[7] Agarwal, R., Oh, B., Fitzpatrick, D., Buynovskiy, A., Lowe, S., Lisy, C., Kriezis, A., Lan, B., Lee, Z., Thomas, A., Wallace, B., Costantino, E., Miner, G., Thayer, J., D'Amico, S., Lemmer, K., Lohmeyer, W., and Palo, S., "Coordinating Development of the SWARM-EX CubeSat Swarm Across Multiple Institutions," in 35th Annual Small Satellite Conference, August 2021, SSC21-WKI-02.

[8] B. A. Cohen, P. O. Hayne, B. Greenhagen, D. A. Paige, C. Seybold and J. Baker, "Lunar Flashlight: Illuminating the Lunar South Pole," in IEEE Aerospace and Electronic Systems Magazine, vol. 35, no. 3, pp. 46-52, 1 March 2020, doi: 10.1109/MAES.2019.2950746.

[9] Andrews, D. and Lightsey, E.G., “Design of a Green Monopropellant Propulsion System for the Lunar Flashlight Mission,” Tech, rep., Masters Report, Dec. 2019.

[10] Smith, C., Littleton, L., Lightsey, E.G., and Cavender, D., “Assembly Integration and Test of the Lunar Flashlight Propulsion System,” AIAA-6.6.2022-1731, 2022 AIAA Science and Technology Forum, San Diego, CA, January 2022.

[11] Littleton, L. and Lightsey, E.G., “Assembly, Integration, and Testing of a Green Monopropellant Propulsion System for NASA’s Lunar Flashlight Mission,” Tech, rep., Masers Report, 2022.

[12] Hart, S. and Lightsey, E. G., **"**Improvements on Two-Phase Cold Gas Propulsion Systems for Small Spacecraft**,"** AAS 23-174, 2023 AAS Guidance, Navigation and Control Conference, Breckenridge, CO, February 2023.